

Research Topics to Validate the Seismic Response of Dams

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Mission Statements

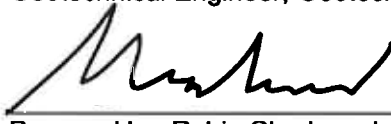
The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Introduction

The objective of this document is to compile an independent list of research topics to validate the seismic response of dams and serve as a reference document for the public to use to identify research topics for the dams sector.

A three step approach was followed:

1. Major stakeholders were contacted, and their input on the research needs to validate the seismic response of dams was solicited.
2. Input was compiled by Larry K. Nuss and Dave Gillette (Reclamation) and Robin Charlwood (consultant).
3. The report was then redistributed to all stakeholders for confirmation of research topics.

Background

The Dam Safety and Security Act of 2003¹ indicates that out of 78,000 dams in the United States, *10,000 have a high-hazard potential, meaning that their failure could result in loss of life or severe property damage*. This particular concern was preceded by the National Dam Safety Program Act² which stipulated that a national program of inspection of dams for the purpose of protecting human life and property should be undertaken as soon as practicable. The program should determine whether a dam constitutes a danger to human life or property, and shall take into consideration the possibility that the dam might be endangered by cracking. Hence, one of the program objectives is to ensure that new and existing dams are safe through the development of technologically and economically feasible programs and procedures for national dam safety hazard reduction.

The goal of the structural analyst is to model the dam as realistically as possible and compute as accurately as possible the response of the dam so that sound management decisions can be made concerning the dam's safety [Reclamation Nonlinear Practices Guidelines]. Sensitivity studies are performed to explore the importance of uncertainties. Overestimating the dam response can lead to unnecessary and expensive modifications. Underestimating the dam response could put downstream populations at an unacceptable or unknown level of risk. Finding the elements that contribute to stability is vital, and key parameters of the analysis and their level of uncertainty must be identified, as well as the sensitivity of the results to various parameters. There must be good communication between all interested parties, including the materials engineers, seismologists, structural engineers, geotechnical engineers, geologists, and management so that the use of

¹ H.R. 4727, Dam Safety and Security Act of 2002.

² National Dam Safety Program Act, Dec. 2000

input from each group and the effect on results is understood. In addition, management must have confidence in results on which decisions are based. At the conclusion of an analysis, the analysts and decision-makers must know how reliable the analysis really is. They should be aware of the strengths and limitations of both linear and nonlinear analyses because, many times, the “true” answer can only be bounded. The final outcome is to decide if the dam is stable and why. Downstream populations depend and rely on potential failure mode assessments.

Structural analysis methods and procedures have greatly improved in recent years. However, it is still not possible to reliably predict the behavior of dams during strong ground shaking due to the difficulty in modeling joint opening and crack formation in the dam body, the nonlinear behavior of the foundation, and the insufficient information on the spatial variation of ground motions around large canyons. Considerable progress has been made in the definition of seismic input, which is one of the main uncertainties in the seismic design and seismic safety evaluation of dams³. Each dam is unique with different canyon shapes, foundation conditions, and material properties. As such, experience gained from a seismic event on a dam provides invaluable and specific data for that dam, but care must be taken when applying to other dams. Observations and measurements from seismic events combined with sophisticated back-analyses that closely reflect reality can be used for further validation of current methods.

Current Procedures to Determine Dam Response

Historically, dam stability analyses for dams have been based predominantly on simple limit state rigid body analyses for concrete gravity dams or elastic analyses in the “working stress” range for concrete arch and buttress dams⁴. These analyses make reference to failure mechanisms based on theoretical predictions.

Concrete dams

The Federal Energy Regulatory Commission’s (FERC) Dam Safety Guidelines Chapter III for Gravity Dams sections 3.4 states their opinions regarding use of analyses for earthquake loadings.

Section 3-3.5 states their objectives for analyses of earthquake loadings:

In a departure from the way the FERC has previously considered seismic loading, there is no longer any acceptance criteria for stability under earthquake loading. Factors of safety under earthquake loading will no longer be evaluated. Acceptance criteria is based on the dam's stability

³ “Earthquake Safety of Concrete Dams and Seismic Design Criteria for Major Dam Projects,” Martin Wieland, Chairman ICOLD Committee on Seismic Aspects of Dam Design.

⁴ See for instance, FERC Guidelines for Dam Safety, Chapter III Gravity Dams or Chapter 11 Arch Dams.

under post earthquake static loading considering damage likely to result from the earthquake. The purpose of considering dynamic loading is to determine the damage that will be caused so that this damage can be accounted for in the subsequent post earthquake static analysis.

Section 3-4.4 states:

As with the application of finite element techniques for static analysis, the reviewer must not lose sight of the purpose of the analysis, ie. to determine whether or not a given failure mode is possible. Finite element techniques assume linear stress strain characteristics in the materials, and almost always ignore the effect of cracking in the dam. Linear assumptions can constitute rather gross errors. For this reason when reviewing the finite element results, the stress output should be viewed qualitatively rather than quantitatively. Finite element dynamic output can show where the structure is most highly stressed, but the stress values should not be considered absolute.

FERC's Chapter XI on Arch Dams section 11-6 discusses procedures for seismic analysis. Section 11-6.1 includes some comments on general principles:

A seismic safety evaluation of an arch dam should be based on the dynamic material properties of the dam concrete, foundation rock, and the energy loss at the reservoir bottom, if applicable. Dynamic modulus of elasticity and dynamic strength of the concrete for earthquake excitation are determined as described in Section 11-3. Damping associated with dissipation of energy in the concrete arch structure and the foundation rock must be consistent with the level of ground shaking, amount of non-linear responses developed in the dam and foundation, and the properties of the foundation rock. For the purpose of safety evaluation, a damping value of 5% or 10% should be used. A 5% damping should be applied to stress and sliding stability analysis of all dams. The increase to a 10% is acceptable for stress analysis of those dams showing energy dissipation through joint opening and tension cracking. The sliding analysis of thrust blocks and abutment wedges, however, should always be conducted using a 5% damping.

In practice, the results can be sensitive to the damping mechanisms and magnitudes. For instance the crest deformation estimates can vary between two and ten times the base level ground motion, depending on dam and foundation material properties, damping etc.

In section 11-8.5 earthquake induced damage to arch dams is discussed.

Concrete arch dams have an excellent record of performance with respect to earthquake motion. No failure has ever resulted from earthquake

damage to an arch dam. It must be realized however, that few major earthquakes have occurred close to an arch dam. Major earthquakes on the order of the maximum credible earthquake are rare events, and in most cases the MCE for a given dam site represents an unprecedented loading condition.

Among some 43 arch dams in 14 countries that are known to have been subjected to significant earthquake excitation (Serafim, 1987), only four have experienced a maximum or a near-maximum earthquake shaking with epicenter close to the dam site. The four arch dams are Pacoima, Lower Crystal Springs, and Gibraltar dams in the United States, and Ambiesta Dam in Italy. Except for Pacoima Dam, which suffered damage during two recent earthquakes, all other 42 dams experienced little or no damage. Following is a description of the performance of Pacoima Dam and other three dams for their historical or design significance:

The case of Pacoima Dam during the Northridge event concludes with the following comments on possible failure modes. These involve the combined behavior of the concrete arch and the abutments: From the damage observed during the Northridge earthquake, earthquake induced failure would probably involve the upper 65 feet of the dam. Such failure could originate from loss of the thrust block caused by a sliding failure of rock masses A and B, or through cracking and opened contraction joints in the dam itself, which could lead to unstable concrete blocks. In either case, a failure of the upper part of the dam more likely would not release the reservoir water, because the intake to the tunnel spillway is 65 feet below the crest. Only concurrent flood and a damaging earthquake might possibly result in a sudden release of water or leakage through opened joints, but more likely the lower part of the dam would remain intact.

Section 11-6.3.3.5 discusses a failure mode involving toppling of a free cantilever:

Fig. 11-6.13 shows the possible failure mode for a free cantilever block defined by two fully opened contraction joints and a horizontal lift joint. For the amount of time that vertical contraction joints are open, the free cantilever's behavior is governed by differential equation 11-6.15

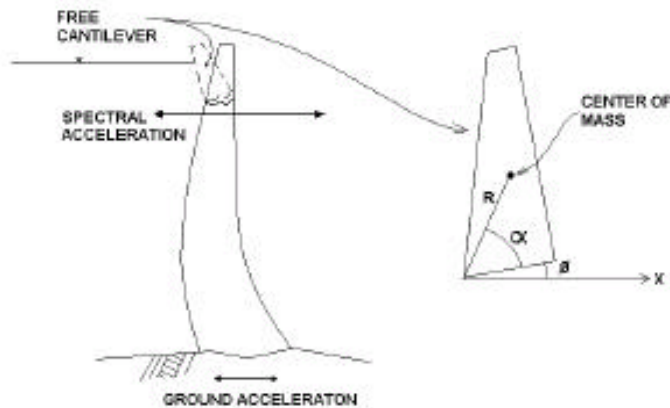


Fig. 11-6.13 Free body diagram of a cantilever with associated forces.

The Bureau of Reclamation⁵ (Reclamation) recently performed laboratory shake table tests on 1/100 scale thin-arch, a 1/150 scale medium-thick arch dams and 1/50 scale gravity dams. The arch dams developed a horizontal joint as shown in the FERC figure and cracks parallel to the abutments forming concrete blocks independent from the dam body. The resulting upper blocks rocked upstream and downstream, rotated in plan, and collapsed downstream as further described below:

- Concrete arch dams are complex three-dimensional shell structures, which are thinner and which have more redundancies than gravity dams. They carry load both in a vertical plane by cantilever action into the base foundation, and horizontally by arch action into the abutments. Therefore, they must be analyzed in three-dimensions to capture the true behavior of the structure. Arch dams require competent rock foundations and are built in narrow canyons, typically limited to a crest length to dam height ratio of about 7 to 1. An arch dam relies on both cantilever and arch action for stability and would not be stable considering two-dimensional cantilever action only, as opposed to a curved gravity dam, which is stable considering two-dimensional cantilever action.

Failure of an arch dam can occur when the applied forces are greater than the resisting forces. Reclamation performed shake table studies on model arch dams using sinusoidal loads to investigate the dynamic failure modes of arch dams. Five models were tested, with different vertical contraction joint/horizontal unbonded lift joint configurations: (1) a model that was monolithic; (2) a model with one vertical contraction joint and no horizontal joints; (3) a model with no vertical contraction joints and one horizontal

⁵ "Investigation of the Failure Modes of Concrete Dams – Physical Model Tests," Dam Safety office, Bureau of Reclamation, Report No. DSO-02-02, May, 2002.

joint; (4) a model with seven vertical contraction joints and no horizontal joints; and (5) a model with seven vertical contraction joints with two horizontal joints. Each of the models failed in a similar manner. A horizontal plane formed by cracking through the dam or along existing unbonded lifts lines. This was followed by diagonal cracks that formed from the crest parallel to the abutments. The diagonal cracks propagated down and connected with the horizontal plane. Geometric differences slightly affected the location of the horizontal plane and the diagonal cracks. Back analysis showed that the horizontal cracks started on the upstream side. Typically the vertical joint along the crown cantilever opened and closed forming a hinge. With sufficient shaking duration, the arch dam failed by blocks rotating downstream similar to a set of swinging double-doors. In the case of the model with seven vertical contraction joints and two horizontal joints, the arch above the upper horizontal joint failed and then the arch above the lower joint failed. The medium-thick arch dam took a lot more earthquake duration to fail than the thin arch.

In addition to consideration of the structure, the interaction between the dam and the foundation and the stability of the foundation and the bearing capacity of the rock itself must be addressed. Failure in the foundation normally occurs by sliding along discontinuities in the rock. The arch will certainly fail if the foundation fails because the dam relies on the foundation for support.

- The stability of concrete gravity dams is caused by their own weight and the strength inherent in the concrete and foundation. Gravity dams, because of their massive size and weight, depend on competent foundations to carry the bearing pressure of the dam and to resist sliding along discontinuities. Most of the time gravity dams are founded on rock although some gravity dams are built on soils. A gravity dam in a wide canyon can be analyzed as a two-dimensional plane strain problem. A gravity dam in a narrow canyon is influenced by the canyon walls and carries load by vertical cantilever-action and by horizontal beam action. In this case, the gravity dam can be analyzed as a two-dimensional plane strain problem, but is more accurately analyzed as a three-dimensional structure. Gravity dams are classified as straight gravity dams or curved gravity dams (sometimes called arched gravity dams). The distinction between a curved gravity dam and an arch dam is that a curved gravity dam is stable without arching action. Typically for a gravity dam to be stable, the slope (horizontal: vertical) of the downstream face must be greater than 0.67:1.0. The intersection of the slopes of the upstream and downstream faces is normally at the dam crest.

Failure can occur within a gravity dam or at the foundation contact when the driving forces are larger than the resisting forces. Driving forces include the static reservoir load, hydrodynamic forces during an earthquake, and the inertia of the dam during an earthquake. Resisting

forces include the internal forces resisting cracking generated by the tensile strength, the forces resisting sliding generated by cohesion, and the frictional resistance from the effective weight of the dam and the friction angle of the potential sliding plane. Dynamic failure is initiated when failure planes form through the structure along weak lift lines, along planes formed by concrete cracking, along planes at the dam/foundation contact, or along discontinuities in the foundation. With sufficient shaking duration, the dam could potentially slide, displacing downstream along a failure plane. Uplift in the failure planes reduces the frictional resistance (by reducing the effective normal stress) and increases the potential for sliding. Drains provide a mechanism to reduce uplift pressures, which increases the stability of the dam and helps arrest crack propagation. Reclamation tested two gravity dam models: one with an existing sub-horizontal crack near the crest and one monolithic dam. The cracked dam failed slowly with the top of dam sliding down the crack. The monolithic dam failed at the same location in the dam but in a brittle manner. When the crack formed across the dam, enough energy was released to topple the top of dam off the dam body in a single instance.

Understanding potential dam failure modes is an essential step in appreciating dam response to earthquakes and validating current analysis methods.

Embankment Dams

Prior to the 1971 near-breach of Lower San Fernando Dam, caused by liquefaction of the embankments hydraulic fill section and sliding of much of the upstream slope, seismic analysis of embankment dams focused largely on the seismic coefficient method, essentially just checking the embankment's yield acceleration against some acceleration value imposed by building code or local practice. The 1971 San Fernando Valley earthquake made it obvious that more was needed. Since then, the main focus of embankment-dam seismic analyses has been assessment of liquefaction potential of loose materials in the foundation or embankment, and analysis of post-earthquake stability. Liquefaction potential is most often assessed using empirical correlations with *in situ* tests such as the standard penetration test or shear-wave velocity.

Post-earthquake strengths are estimated using laboratory tests and/or additional empirical correlations with *in situ* tests. There are rather severe difficulties with either of these approaches. Laboratory stress-strain tests can only deal with small samples and cannot replicate the effects of material heterogeneity or of certain large-scale phenomena such as migration of excess pore-water pressure from loose, liquefied material into denser material, or formation of a water film at the base of a low-permeability layer overlying a layer of loose sand. *In situ* can be "calibrated" against field behavior, but the number of earthquake case histories is limited, and there is only so much information that can be gained from back-

analyzing from known behavior. For example, if a slope did not fail, that information provides only a lower bound on the strength of the soil.

For larger embankments potentially subjected to severe earthquake loadings, deformation analysis is gaining prominence in practice. It is recognized that even a dam with an adequate post-earthquake factor of safety can undergo large dynamic deformations during the earthquake. Simple Newmark-type sliding-block analysis (or a chart solution based on it) has been used since the 1960s, but advances in computing power have allowed finite-element and finite-difference codes such as FLAC and PLAXIS to be developed and used.

At present, the sophistication of computational methods for deformation and stability exceeds our ability to determine the material parameters needed; therein lie our most pressing research needs.

Industry Move towards Risk Based Methods

Recently, there has been an important swing in methodology for dam safety assessments towards risk based methods⁶. Reclamation have been applying such methods since the mid 1990s⁷ to their over 400 large dams, FERC introduced risk concepts in their 2004 [Dam Safety Performance Monitoring Program](#)⁸ for the over 2,400 Licensed dams under their jurisdiction and the US Army Corps of Engineers have introduced risk analysis methods to their over 600 large dams in 2005⁹.

These methods place an explicit emphasis on “Potential Failure Modes Analysis”. That is they require identification of the detailed modes of failure, understanding of the progressive behavior and mechanisms of the dam as failure develops, the “reserve strength” that may be available beyond the nominal limit state strength of the dam usually characterized by a “fragility curve”, and the “brittleness” of the dam, that is the extent to which failure may occur quickly. In addition, the surveillance and monitoring of the dams is now being refocused on “performance parameters” that will provide early warning of the development of a failure mode and the assignment of threshold and alarm level values of these parameters.

The FERC Dam Safety website¹⁰ in the New Approaches for Dam Safety Section includes the following statements regarding the critical role of the understanding of failure modes:

⁶ ICOLD Bulletin 130, Risk Assessment in Dam safety, 2005

⁷ USBR Guidelines for Achieving Public Protection in Dam Safety Decision Making, 2003.

⁸ FERC Hydropower - Chapter 14 of the Engineering Guidelines

⁹ USSD Annual Meeting 2005, An Overview of the USACE’s Screening for Probabilistic Risk Assessment for Dam safety Program, San Antonio, TX.

¹⁰ <http://www.ferc.gov/industries/hydropower/safety/guidelines/dspmp/background/new-approaches.asp>

New innovative approaches are resulting in effective and efficient additional tools that dam owners, engineers and regulators can use to properly monitor, evaluate, and maintain safe operating dams.

Where potentially unsafe conditions could develop, if not properly monitored or remediate, these approaches will: (1) identify possibly overlooked potential failure modes that need to be examined; and (2) determine whether any additional features would be required if the dam was designed today.

Therefore, this is the appropriate time to transition into the next era of the FERC Dam Safety Program that includes a detailed, comprehensive Dam Safety Performance Monitoring Program to ensure that potential failure modes are properly identified and addressed.

This will alleviate the false sense of security that is in place at sites where developing unsafe conditions have not yet been detected under traditional safety reviews.

New risk based approaches require a major extension of dam safety analyses up to and including the failure states. The understanding of the mechanics of failure in “static” loadings, including self weight, hydrostatic pressures, ice loads, flood loadings, etc., is still surprisingly limited. For instance, the modes of sliding or overturning failure are still subject to debate for relatively simple structures such as gravity dams¹¹.

In the case of dynamic loadings cause by earthquakes, the knowledge of actual behavior during earthquakes and of failure mechanisms is limited.

The only known case of a concrete dam severely damaged by an earthquake to date is the case of Shih Kang dam in Taiwan during the Chi Chi 1999 earthquake. The performance of concrete dams during earthquakes has been documented by the USSD Committee on Earthquakes and Dams¹². This record shows that the number of recorded cases of large ground motions at dam sites is limited and the magnitudes of ground motions has seldom been close to the design values. So, even though the performance record appears good, the fact is that this apparent good performance of dams is mainly because of the fact that few major earthquakes have occurred near enough to dams to provide a real test of their resilience.

Dam safety analyses of the effects of earthquakes currently rely on a) assumptions regarding the failure modes; b) simple rigid body or simple elastic models to model potential failure modes; and c) a limited data base of failure or damage case histories for calibration of the models.

¹¹ Victor Saouma et al's EPRI work on fracture mechanics for failure of gravity dams

¹² USSD Observed Performance of Dams during Earthquakes, Vol I, 1992 and Vol II, 2000.

Given this situation, there needs to be improvements and advancements in our understanding of the reliability of existing models of behavior in the working stress load ranges and particularly of the potential failure modes of dams in order to provide the tools to allow the application of risk based methods of dam safety assessment to be effective. There also needs to be validation testing that analysis methods can be benchmarked against.

Historical Levels of Funding Seismic Dam Research

Historically, major research investigating the seismic response of dams has been funded by the National Science Foundation (NSF), the Electric Power Research Institute (EPRI), the Bureau of Reclamation (Reclamation), and the US Army Corps of Engineers (USACE). Private engineering companies, regulators, and electric power companies have funded selected projects to a lesser degree. The Tokyo Electric Power Company, since 2000, has provided significant funds to the University of Colorado to develop computational tools for the non-linear structural analysis of dams.

However, it is safe to say that in the United States:

1. There has never been a major comprehensive research program on the seismic performance of dams.
2. There has not also been in the last 10 years any significant and sustained research program on this topic.

This is to be contrasted with a major effort in the European Community through the Network of Integrity Assessment of Large Concrete Dams:

<http://nw-ialad.uibk.ac.at/>

and in Japan through the MITI project (headed by Professor Horii) following the Kobe Earthquake, and through private sector research funds:

<http://www.waterpowermagazine.com/story.asp?storyCode=2032485>

Survey Responses

Feedback obtained from several of the contacted agencies, companies, and consultants (see Section 4) resulted in the following list of research needs that require particular attention.

General

Inelastic Behavior of Dams

There is an increasing interest in the inelastic non-linear behavior of concrete dams including roller-compacted concrete dams (RCC) and embankment dams

including concrete faced rock-fill dams (CFRD) under shaking from extreme earthquake ground motions. There is also interest in dam response due to movements under the dam along fault lines. There are faults that were considered inactive at the time of the design of a dam that are considered potentially active today.

Seismic Excitation

The seismic response of dams depends on the input ground motions exciting the structure. Realistic and appropriate seismic input must be developed to accurately and confidently predict the seismic performance of a dam with minimal uncertainty.

1. Develop better estimates of near field earthquake shaking, current ones seem unreasonably high.
2. Determine the appropriate way to apply spatially varying ground motions to computer models.
3. Appropriate ground motions must be used when dams exhibit non-linear behavior and the natural frequency of the structure changes.
4. Application of seismic motions and wave travel through embankment
5. Selection of ground motion parameters for routine projects where full dynamic analyses are not being pursued is an area in which many regulatory reviewers, owners, and even consultants frequently have an inadequate understanding. This involves developing simplified approaches in low-seismic areas.

Post-earthquake validation analyses (Back analyses)

The best way to determine the seismic performance of dams and validate structural analyses is to capture the response from real dams subjected to real earthquakes. Then perform post-earthquake structural analyses and compare calculated to observed response to see if current techniques capture the dynamic response of the structure. Unfortunately, many dams have experienced seismic loading, but the response of the dams were not captured for either: 1) lack of instrumentation, 2) inappropriate or minimal instrumentation, or 3) instrumentation failure. There should be a long-term program to instrument existing dams with a high probability of being shaken by severe earthquakes. There should be sufficient instrumentation to capture the response of the dam from base to crest and along the crest, to capture the free-field ground motions around the canyon, to capture hydrodynamic pressures in the reservoir and foundation, and to capture video to observe failure mechanisms, crack development, block movements, and seepage water.

Validation of structural analyses

Validation of structural analyses results through complimentary pre-test and post-test analyses of gravity dams, arch dams, spillways on embankment dams, and embankment dams. The issues are to determine:

1. Failure modes
2. Initiation of failure and post-seismic damage and stability

3. Deformation and liquefaction of embankment dams
4. Soil-structure interaction loads and deformation of spillway walls next to embankment dams

Probabilistic methods of analyses

Many dam owners and regulating agencies are moving toward risk based approaches for managing the large inventory of dams. Risk-based methods require the following:

1. Develop strategies to achieve risk reduction goals for structures potentially subject to extreme loading conditions.
2. Development or refinement of processes to estimate the consequences of large events on structures and communities.
3. Develop methods to incorporate traditional engineering analysis tools into new risk analyses.
4. Develop input distributions for concrete and foundation properties to put into reliability functions.
5. Determine the impact of dam failure on society.
6. Determine what the perception is of dam failure on the general population.
7. Determine how the engineering community should factor societal aversion in to risk analyses.
8. Further develop Fragility Curves techniques for dams.

Simplified Methods of Analyses in Low Seismic Areas

One of the issues commonly faced in the Eastern U.S. is the appropriate level of analyses of dams in areas of relatively low seismic areas. Some form of simplified seismic analysis is typically performed for many projects to demonstrate that seismic does not appear to be the governing load case. Many times full dynamic analyses are typically far beyond our usual scope for most practicing engineers. Issues include what method(s) of analyses should be deemed acceptable, at least as a screening tool, and how reliable are such assessments in terms of overall risk. Further, there is little in the way of industry-accepted software to facilitate the more simple analyses. Consultants typically rely on internal spreadsheet analyses for pseudo-static or Chopra's method. Some University codes incorporate pseudo-dynamic routines, but the codes are developed as a teaching tool rather than commercial applications. A more unified set of tools that is peer reviewed would be advantageous.

Embankment Dams

Liquefaction in Soil with Gravel

There needs to be validated methods for determining liquefaction potential in soils with gravels. At present, the main tools are the Becker Hammer Penetration test (BPT) and the shear-wave velocity. Both tools rely on empirical correlations, very complex ones in the case of the BPT. Measured at small strains, the shear-wave velocity is sensitive to aging effects and weak cementing that can affect the measured velocity without significantly changing the behavior at larger strains.

Liquefaction in Soil

Some embankment dams and foundations can liquefy during seismic events making the embankment unstable. There are many factors that affect liquefaction: moisture content of the soil, soil characteristics, gravel content, density, and level of shaking. There is a need for reliable techniques to determine if soils at a dam site are liquefiable for specific seismic loadings. Some issues involve:

- Unreliability and discrepancy of current methods: Standard penetration Tests (SPT), Becker Hammer Penetration Tests (BPT), cone penetration tests, and shear-wave velocity tests
- Validated soil analyses models and techniques
- Liquefaction potential at large strain rates
- Reliable field tests for soils with gravels (see discussion above)
- Stiffness and modulus reduction
- Load redistribution
- Determine the value of C_n in liquefaction analyses to derive the N_{160} under high confining pressures outside Seed's recommendations.

Subtasks

1. Develop strategies to calculate post-earthquake shear strength for soils, particularly those with SPT blow counts between 15 and 25.
2. Develop methods to increase confidence in non-linear modeling of embankments.
3. Develop easily adaptable methods to model pore pressure changes and strength reductions for dynamic analysis using FLAC.
4. Develop methods to advance the state of knowledge concerning seismic loads on spillway walls and modeling the soil-structure interaction related to spillway walls.
5. Develop methods to evaluate failure potential and probabilities for structures that deform but do not lose all freeboard.
6. Contribute to the development of methods to find concentrated seepage through embankments.

Transverse cracking of embankment dams caused by earthquakes

Transverse cracking of dams and dikes caused by earthquakes could result in embankment failure by erosion if the cracks persist below the reservoir level. At present, evaluation of crack potential is primarily by subjective judgment, with consideration given to abutment geometry and the level of compaction in the embankment, both of which were important in causing the deep cracks at Austrian Dam in the 1989 Loma Prieta earthquake.

Case histories are few, in part because of the infrequent occurrence of major earthquakes, and in part because of the difficulty of getting good quality field observations, even though one may have good contacts. The data are often not gathered in the rush to get the dam back into service. There would be significant

value in setting up a long term systematic gathering of quality data in dams which experience earthquakes.

The analysis of the potential for cracking also warrants work. It is not a simple matter as it really requires 3-dimensional structural analyses because earthquakes cause spreading in the upstream-downstream direction, which in turn may promote movement towards the valley center and lateral cracking, in addition to the effects of cross-valley movement and settlements that could cause tensile strain at abrupt changes in abutment slopes. It is tied up with statically induced stresses which may have cracked the dam, or left it in a "fragile" state with low stresses (e.g. against walls, over large irregularities in the foundation profile, or across the cutoff wall).

One important area of research would be to evaluate designs using practical solutions to mitigate the adverse effects of transverse cracking.

Levee

Levees are a special form of embankments that are vulnerable to seismic loads and overtopping as evident by the Hurricane Katrina in the New Orleans area. The same devastating results could occur in an area with the failure of a levee during an earthquake. Two issues that should be investigated are 1) the dynamic stability of levee walls, 2) a technology transfer between seismic embankment design and levee design, and 3) the development of a reliable geophysical method for interpolating material properties between levee explorations holes, which are usually on 100 feet or more centers.

Modulus and Damping in Embankments Dams

There should be validated modulus and damping values for high dynamic stresses in embankments. Current values used in structural analyses produce high crest accelerations that do not match what is measured during actual earthquakes.

Post-earthquake strength

There is an issue with the post-earthquake strength of materials that become liquefied in the sense of high pore pressure initially, but dilate with monotonic strain. (Roughly speaking, N1-60 of 15 to 25, beyond the limit of Seed and Harder's data, but not dense enough to be assigned drained strengths with any confidence.) This is an issue for embankment dams on moderately loose foundations, since a large "static" shear load would remain on the foundation after the shaking is over.

Heterogeneous nature and large scale effects

The gross-scale behavior of heterogeneous materials is not well understood at all. Laboratory-scale tests can yield good models for each small specimen tested, but the material a few inches away, vertically or horizontally, may have different properties.

Concrete Dams

Failure modes

As stated above, seismic failure modes of arch, buttress, and gravity dams are not well understood because so few concrete dams have experienced high levels of seismic shaking. Failure modes could be determined through shake table testing, large scale field testing, or monitoring of existing dams with high probability earthquakes. Some of the issues are the effect of the height of the dam, the thickness of the dam, the vertical contraction joints, the horizontal lift lines if unbonded, and the canyon shape. The length of time it takes failure to occur greatly affects the downstream evacuation and potential loss of life.

Validation of structural analyses

Validate structural analyses through testing and complimentary pre-test and post-test analyses of failure modes of dams. As stated above, the computed response of a dam is greatly affected by the damping and the material strengths used. Although the numerical capabilities are advanced, the determination of input variables in the non-linear ranges and approaching failure is currently fraught with uncertainties. A data set of scale tests, large scale tests, and instrumented existing dams are needed to validate and calibrate current structural analysis models and techniques. The issues are the initiation of damage, the appropriate level of damping, the correct application of seismic input for large canyons, and the non-linear response of the dam given geometric non-linearity (contraction joints and lift lines) and material non-linearity (concrete and rock). Ultimately a concrete dam fails by large movements of concrete or rock blocks by sliding. There is a need for validated sliding simulations to accurately predict the amount of block sliding.

The International Commission on Large Dams (ICOLD) has sponsored many numerical benchmark analyses. The benchmarks pose a problem associated with a dam and analysts from around the world address the problem with various computer codes. This provides a comparison among the computer codes and the approach used, but does not provide validation of the results.

Damping

There is uncertainty concerning the amount of damping to use in the dynamic structural analysis of a dam for large seismic events. The profession currently accepts from 5 to 10 percent of critical viscous damping. Using different levels of damping or incorporating radiation damping in the foundation during a seismic analysis of large arch dams can yield drastically different results. Computed stresses in the dam can be on the order of five times different depending on the damping mechanisms and magnitude of damping used or not used. There is reluctance by the profession to use programs incorporating radiation damping resulting in too large of dam response. This lends itself to conservative stress and displacement computation that could result in unnecessary and expensive modifications to the dam. This should be resolved. The issues are:

1. Validate and correctly model all damping mechanisms for all levels of seismic shaking: radiation damping, friction along sliding discontinuities (cracks, unbonded lift lines, contraction joints, foundation bedding), and material damping.
2. Investigate appropriate mechanisms for modeling damping in analyses. Rayleigh damping may not be appropriate when modeling large displacements or sliding. Therefore, different damping techniques besides Rayleigh damping need to be developed.

Foundation stability analysis

Concrete dams transfer tremendous forces into the foundation and are stable because the foundations can carry the imposed loads. The designs of older dams were mainly concerned about seepage through the foundations and not necessarily stability of the foundation. It was believed foundations were so massive not to be of concern. Geotechnical engineering greatly advanced in the mid-1970s as a result of some dam failures. As a result, some dams are found to have questionable foundation stability. There is a need to advance the state-of-the-art in foundation stability analyses for concrete dams. The issues are that currently, foundation stability is performed in an uncoupled manner. This involves computing forces from the dam into the foundation. These forces are then used in a separate and independent foundation analyses. This is not close to reality because the dam and foundation act together as one unit. The desirable method is to perform a coupled dam/foundation modeling so foundation discontinuities are incorporated in the analysis. Once the dam and foundations are modeled as one unit, validation testing is necessary to determine the correct amount of sliding that can occur.

Shear keys, unbonded lift lines, and contraction joints

Concrete dams are built with vertical contraction joints to control thermal cracking of the dam. Shear keys may or may not be designed into the contraction joint. The amount of strength the shear keys provide during a seismic event is unknown.

Validated concrete material models and damage levels

Concrete is a non-linear material with a curved stress-strain relationship. At low levels of induced stress the concrete remains linear and linear-elastic material models for the concrete in structural analyses are quite appropriate. However, large seismic events can overstress the concrete causing cracking and non-linear behavior. When this happens, structural analyses using non-linear material must be performed to realistically capture the response of the dam and redistribution of load. This is important to quantify the level of damage during an earthquake for stability during the event and for the level of damage after the earthquake to assess post-earthquake stability. The issues that need to be addressed are:

1. There are many concrete cracking and nonlinear models that have been developed that are based on fracture mechanics and smeared cracking approaches. It is difficult for a practicing engineer to know what models to use and what models produce the more accurate results. There should be an assessment of the available concrete models and recommendations on what models are the most realistic.
2. Once the most realistic non-linear concrete models are determined, the concrete models should be developed in modular form to easily incorporate in any finite element structural code.
3. There is a need to develop concrete material models that are not affected by the size of the finite element mesh being used.
4. Once appropriate and validated computer material models are identified for concrete, laboratory test protocols need to be developed to measure each input parameter. Sophisticated non-linear structural analyses are not really appropriate with assumed material properties or material properties that cannot be measured.
5. Protocols are needed for the tensile strength of concrete under fast and repetitive loadings. There is uncertainty if the direct tensile strength or the splitting tensile strength of concrete should be used.

Dynamic uplift during and after an earthquake

Current thinking and criteria in the dams sector is to assume the uplift profile under a dam is the same before, during, and after a seismic event. This may or may not be correct or conservative. Considerable research has been done looking at uplift pressures along cracks and discontinuities during seismic events. There still seems to be uncertainty during a seismic event on how fast reservoir water can enter discontinuities, the impact of water getting into discontinuities during an event, the effectiveness of drains, and what the post-earthquake uplift profile should be. This may sound simple but there are active debates about how this should be considered in the post-earthquake case and to what extent should uplift be included in an earthquake induced crack?

Silent Boundary Conditions:

Develop better non-reflective boundaries at extents of foundations in finite element models that have mass in the foundation. Most non-reflecting boundaries in finite element programs use simplified boundaries composed of dampers that reduce waves perpendicular to the surface. The boundaries may not be as effective for waves at acute angles. As such, the foundation extends are positioned many dam heights away from the dam so returning waves do not corrupt the solution. Smaller foundation models could be used with more effective silent boundaries. The computation time and solution accuracy could save considerable time and assure more realistic answers.

Effects of spatially varying earthquakes

Dams can be large structures in large canyons. Seismic waves vary in phase and amplitude as the energy travels around the canyon. The effect on dam

response of this spatially varying seismic energy around a canyon is unknown. There is a need to determine the effect of spatially varying seismic waves on dams. Once the effect is known and is determined to be important, analytic techniques need to be developed to incorporate this effect in structural analyses.

Displacements of gravity dams

There needs to be a reliable method to determine the amount of sliding that can occur in concrete gravity dams under earthquake loading. There also needs to be an assessment on how much sliding is acceptable. A concrete dam may be stable after a seismic event with a small amount of sliding. There are many factors that affect sliding such as the reduction of shear strength, the increase of uplift and water flow into discontinuities, the effectiveness of drains, the magnitude of post-earthquake events, level of damping, duration of the earthquake, and the damaged state of the dam.

Simplified methods

In embankment dam engineering there are a number of empirical or simplified methods to determine how much settlement will occur under earthquake. These methods can be used where there is a good margin of safety to losing freeboard. There are currently no similar methods for concrete gravity dams. Some engineers use a Newmark type approach developed to assess the likely amount of sliding. From this they assess how much loss of strength will have occurred during the displacements, and assess post earthquake stability. Newmark type analyses are based on simplified analyses and may not have been calibrated against more rigorous methods. There could be significant cost savings if simplified and rigorous methods were generally available.

Strengthening of Concrete Dams

There needs to be studies to determine effective and economical methods to strengthen concrete dams where risk reduction actions are justified based on their ability to resist anticipated loads. Current methods involve lowering the reservoir, reshaping or thickening the dam, post-tensioning, and anti-seismic steel belts. Dampers, although used in buildings, have not been used in large dams. The effectiveness of these rehabilitation methods could be validated with large scale tests.

Spillways

Gated Spillway Crest Structures

Spillways are sometimes built on the sides of embankment dams with the embankment material placed against the spillway walls. Gated spillways can store water on the spillway walls. During an earthquake the walls can deflect and permit a seepage path between the walls and embankment material that could breach the embankment. There is a need to determine the response of the spillway walls during an earthquake and validate current computer software. Some issues involve:

1. Spillway walls vary in height from a few feet high to 50 feet high. This greatly affects the dynamic soil pressures and distribution of pressures applied to the walls.
2. The designs of the walls vary. The walls can be counter-forted, cantilevers, or framed.
3. Many times spillway walls are designed using 2-dimensional simplified structural analyses. During an earthquake, 3-dimensional effects could have a large effect on the stability and deflections of the wall.
4. There is little known about the amount of damping in the spillway wall embankment system.
5. Non-linear material soil models should be used to determine the response of the soil during an earthquake.
6. The spillway walls can bear on soil or rock foundations that can change the dynamic response of the walls.

Hydrodynamic loads on spillway gates

Many spillways are built at the crest on concrete dams or high on the abutments of embankment dams. The gates can be radial gates (tainter gates), fixed-wheel gates, or drum gates. The gates can be positioned along the upstream face of the dam or can be set back from the face in a cove. When the gates are set back in a cove, there is a question on how much hydrodynamic pressure is exerted on the gate during an earthquake. Current practice is to use Westergaard's added mass using the full height of the reservoir in the computation. This may be too conservative and causing gates to be way over designed.

Innovative rehabilitation schemes

Once problem spillways are identified, rehabilitate schemes that are innovative, effective, and economical solutions is needed.

Benefits of Testing at Large Scale Facilities

Past methods of testing at small scale

The dam industry has used several approaches in the past to study some of the listed research topics, including:

1. Dynamic excitation tests on dams – There have been various attempts to excite dams in the field with eccentric mass shakers, explosives in the foundation, and air poppers in the reservoir. While these tests provide interesting data on low amplitude responses, damping values etc, their applicability to large earthquake events are limited. Higher level tests are required to capture damping levels, cracking patterns, and the effect of contraction joint opening and closing.

2. Laboratory shake table tests – Laboratory shake table tests have been performed on model dams, but most of the tests have been small. Large shake tables allow realistic ground motion inputs and fewer similitude problems when scaling down a test. There is uncertainty whether small scale test results truly represent the full scale dam.
3. Small scale laboratory centrifuge tests – Small scale centrifuge tests allow improved theoretical scaling of model tests, but their applicability to full scale prototypes is limited. The models are too small to accurately model large aggregate in mass concrete used in concrete dams or soil used in embankment dams. Sometimes the modeled dams do not fail as would a real dam.
4. Strong-motion instruments – A few dams with strong motions instruments have captured the response of the structure during an earthquake. The obvious disadvantage of this method is the uncontrolled time of occurrence, magnitude, and frequency content of the earthquake event. However, this is the ultimate scenario for capturing the true response of a structure during an earthquake. There needs to be a comprehensive, well thought out, and implemented plan to measure the in situ response of dams during seismic events. This requires funding, maintenance, and patience, but the rewards are great.

Large scale facilities

The National Science Foundation through its Network for Earthquake Engineering Simulation (NEES) program has equipment for large scale testing. These facilities and others not identified in this document could be used. Performing tests at facilities, such as NEES, provides the benefit and advantages of large scale testing as illustrated in Figures 1 through 3. Because dams are so large, there can be too many similitude problems testing at smaller scales. Large scale testing has the benefit of minimizing the scaling effects when testing small models. Large scale testing provides a major step in developing and validating appropriate computational capabilities for earthquake design and safety evaluations of dams and spillways. Validation ensures that the software does what it is intended to do and accurately and realistically predicts the response of a dam and the failure modes of a dam.

In particular the following NEES facilities could be used:

1. Large shaking table at the University of California at San Diego:
<http://nees.ucsd.edu>
2. Centrifuge mounted shaking table at the University of California at Davis:
<http://nees.ucdavis.edu/>
3. Fast Hybrid testing facility at the University of Colorado at Boulder:
<http://nees.colorado.edu>
4. Large scale shakers at the University of Texas at Austin:

<http://nees.utexas.edu>

5. Mobile field laboratory at the University of California at Los Angeles:

<http://nees.ucla.edu/>

The following is a list of issues that might be resolved with large scale tests.

Benefits and improvements from large scale testing

Material properties

Mass concrete properties

Concrete dams are made with mass concrete consisting of maximum sized aggregates typically up to 6-inches in diameter. Small scale tests require modifying the concrete to approximate similitude requirements (aggregate size and material properties: modulus, density, strength) such that the scaled concrete may not act and respond like real concrete. Concrete used in large scale models can be made with larger aggregates that more accurately match real mass concrete properties. In this way, the response of the dam and failure mechanisms can be more closely modeled than with small scale models.

Concrete tensile threshold

There are different tests to measure the tensile strength of concrete: splitting tension test, direct tension test, and 3-point bending test. Raphael discussed the differences in tensile strength in his 1983 paper¹³. Constitutive models for concrete in finite element programs require one value for the tensile strength of concrete. It is not clear which tensile strength value to use in structural analyses. This value is important because the onset of concrete cracking is the initiation of failure in a concrete dam. Also, the dynamic tensile strength is probably different than the static tensile strength. Since the concrete used in large scale tests more closely matches real mass concrete and the tri-axial state of stress, the initiation tensile strength of concrete can be determined.

Constitutive models

Current constitutive models for concrete in finite element programs may or may not accurately model mass concrete. Once large scale tests are run with closely matching mass concrete, back-analyses can be performed with constitutive concrete models and determine how accurately the failure mechanisms can be predicted. Running pre-test structural analyses can show how accurately the current state-of-art is at predicting failure. The formulation or material inputs for the constitutive concrete models can be adjusted as necessary.

Fracture, shearing, and sliding

Tensile cracking of concrete in the dam and fracture mechanisms represent damage in the structure, but do not necessarily constitute failure of the structure. For failure to occur, blocks or portions of the dam need to move out from the

¹³ "Tensile Strength of Concrete," Jerome Raphael, Title No. 81-17, ACI Journal, March 1984.

structure and release the reservoir. To move, the blocks must be removable (form base and side planes) and exhibit more sliding driving forces than resisting forces. Large scale tests can show cracking patterns, the formation of removable blocks, and the amount the blocks might move. Back-analyses can compute the shear strength developed along the slide planes from friction and asperities along the slide planes.

Soil

Some concrete dams have embankment wrap-around sections and some spillway walls abut against embankment dams. Large scale tests could determine the level of damping exhibited by the soil, the dynamic pressures induced by the soil on the structures, and the potential to develop seepage paths along the contact between the concrete structure and embankment.

Loading

Uplift

Large scale tests, being more realistic, can probably reduce the uncertainty concerning questions of uplift and water flow in seismically induced cracks. There are similitude problems with modeling water pressures and flow at small scales. This would not be an issue at full scale.

Seismic inputs

Ground motions are oscillatory in nature with multi-directional high-energy spikes of varying magnitude, duration, and frequency. A series of tests or analyses could be performed to determine the sensitivity of the structural response to changes in seismic input. Ground motions with the following characteristics could be sampled: strong single pulses surrounded by smaller pulses, multiple strong pulses, short duration, long duration, frequency content matching linear structure, frequency content stronger in non-linear structure, or frequency content matching smooth response spectra.

Spatially varying seismic motions

Dams can be hundreds of feet high and wide. As such, seismic energy can vary spatially around the canyon and around the dam. It is unknown how seismic spatial variations affect the response of dams. The energy might become incoherent and out-of-phase enough to reduce the dam response. Or, the motions might become in-phase and induce adverse impacts on the structures, more than currently being considered. Large scale tests may be able to simulate this action and shed some light on the subject. Also, data from a series of micro-seismic and strong motion instruments around canyons would be useful.

Hydrodynamic interaction

Considerable research has studied the hydrodynamic interaction of the dam – reservoir – foundation system. There is some uncertainty as to how accurately the reservoir topography should be modeled, how accurately the new fluid finite elements simulate water, and is the reflection of seismic energy along

the reservoir bottom being modeled correctly. Some specialized finite element programs incorporate a reservoir-bottom reflection coefficient to account for the absorption of seismic energy. General purpose programs do not have this coefficient. The impedance contrast and wave transmission between the foundation rock and reservoir water is automatically incorporated because rock and water have different material properties. However, silt along the reservoir bottom affects this absorption and should it be modeled when the coefficient is not used? The large scale tests should provide answers.

Damping (elastic to damage)

There are many damping mechanisms in the dam – reservoir – foundation system: hysteretic damping as materials strain, heat and friction damping as blocks slide, impact damping as blocks pound together, and radiation damping as energy transmits out from the structure. Typically 5 to 10 percent viscous damping is used when performing linear-elastic analyses of dams. Different computer codes use various damping algorithms. Rayleigh damping can go unrealistically high when the analyses goes non-linear. The level of damping in a dam is uncertain since so few concrete dams have captured the non-linear dynamic response during an earthquake. Measuring the damping in a large scale test when the model is undamaged and damaged can shed some light on the level of damping.

Radiation damping and impedance contrast

There is some uncertainty on the amount of radiation damping that can occur in the foundation of a concrete dam and on the effect of differing material properties between concrete and foundation rock. The amount of damping and response of the dam in structural analyses might be overemphasized if the foundation modulus is considerably less than the concrete modulus and if the foundation modulus is increasing with depth (weathering and jointing reduce, and confinement and density increases). It is unknown at this time how to determine the appropriate amount and appropriate mechanism to incorporate radiation damping in structural analyses of dams.

Finite element models

Validation and benchmark tests

The most beneficial aspect of large scale tests is the data that can be used to validate structural analyses. Large scale testing offers the most realistic data without testing a real dam. Scale effects are minimized because the materials in a large scale are real and not grossly modified to mean similitude requirements. The large scale tests act realistically. Finite element analyses can be validated by modeling the “model” and confidence is developed when the “model” is as close to realist as possible. The set of validation tests and data generated from large scale tests can be used by others and in the future.

Detailed study of dam features

Many of the special features inherent to dams can be more accurately incorporated in large scale models: shear keys, contraction joints, lift lines, and foundation discontinuities. Special features are too unrealistically small to incorporate in small models. Failure mechanisms are more realistic when all the features of dams are modeled.

Coupled dam/foundation interaction and block stability

Some concrete dams have failed because of instability in the foundation. Current state-of-practice is to analyze the stability of rock wedges using an uncoupled approach. Forces from the dam into the rock wedges are computed and then applied in separate analyses to the rock wedges. The uncoupled analyses ignore the redistribution of dam loads as the rock wedges move and ignore the change in seismic energy into the rock wedge as it decouples from the foundation. Foundation discontinuities can be modeled in a large scale test and the interaction effects can be observed.

Silent boundary condition

Finite element models incorporate a limited portion of the foundation away from the structure. The limited foundation extent must model the foundation as if it was much larger and the “imaginary” finite element boundary is not present. Many of the non-reflective boundaries in current finite element codes use simplified approximations and allow some seismic energy back into the model. Large scale models can position the foundation extents away from the structure in question.

Dynamic response

Natural frequencies

The natural frequency of a dam changes as the structure is damaged and goes from a linear state into a non-linear state. The amount of change that the natural frequency undergoes is a function of the damage level and is not known. As the natural frequency of the dam changes, earthquakes affect the structure differently depending on the frequency content of the ground motion. The natural frequency of an undamaged and damaged large scale dam model could be measured. The measured natural frequency will be more accurate with larger scale models made with realistic materials. This knowledge would greatly help seismologists select appropriate ground motions.

Failure mechanism and rate of failure

The greatest benefit from a large scale model is to capture realistic failure modes and rates of failure. For structural analyses to be beneficial for dam safety decision makers, structural analyses must be accurate, realistic, and defensible. The rate of failure is important for emergency managers and warning downstream populations of impending danger in the event of progressing failure. Large scale tests would provide invaluable data and insights into this area.

Sliding

For dams to fail, blocks must slide out of the way and release the reservoir. The amount of sliding is a key factor in determining if a total failure will occur during or after a seismic event. Dams may be able to accommodate small movements of less than a few inches. Horizontal movements larger than 6-inches may pinch off drains in the dam and foundation and change the uplift profile under the dam and cause instability. Waterstops along the contraction joints may fail and the flow of reservoir water through the contraction joints may cause problems. This amount of movement may cause other features in the dam to fail such as spillway gates, penstocks, or outlet works pipes; or cause piping along dam to embankment interfaces. Large scale models would shed some light on sliding failure mechanisms.

Displacements / acceleration

During an earthquake, through cracks and unbonded lift lines cause a decoupling of the structure above and below the discontinuity. As such, the seismic energy changes at the discontinuity. Large scale tests can show how the structural response changes when damage occurs and if structural analyses are computing the response correctly.

Post earthquake stability

A dam may be damaged during an earthquake. Emergency managers must determine the stability of the dam in the post-earthquake condition and the stability of dam during aftershocks. Large scale tests would give a good indication of the damage during an earthquake and the post-earthquake stability.

Soil-structure interaction

Soils are difficult to model at small scales. The preferred method is to model the soil in a centrifuge or at full scale. The NEES facilities provide these capabilities and would provide a significant increase the understanding of soil-structure interaction and provide an accurate representation of this interaction without the negative aspects of small scale effects.

Contacted Stakeholders

The following stakeholders were contacted by email and telephone.

Federal Agencies

Bureau of Reclamation
Denver, CO

Larry K. Nuss – Structural Engineer
David Gillette – Geotechnical Engineer
Brian Becker – Deputy Chief, Dam Safety Office
Chuck Hennig – Research and Technology, Deputy Director
Lowell Pimley, - Chief, Civil Engineering Services Division

US Army Corps of Engineers
Vicksburg, MS
Michael Sharp

Federal Energy Regulatory Commission
Washington, DC
Bruce Brand

Department of Homeland Security
Washington, DC
Enrique Matheu

Navy Facilities Engineering Service Center
Port Hueneme, CA
Javier Malvar

State Agencies

California Department of Water Resources
Sacramento, CA
Mark Schultz

Private Consultants

Robin Charlwood
Seattle, WA

Eric Kollgaard
Concord, CA

Larry Von Thun
Lakewood, CO

C.H. Yeh
Chicago, IL

Engineering Firms and Utility Companies

ACRES International
Buffalo, NY
Dan Curtis

Gannett Fleming, Inc.
Harrisburg, PA

Boyd Howard

HDR Engineering, Inc
Folsom, CA

Peter Hradilek

MWH

Bellevue, WA

Glenn Tarbox

Quest Structures

Yusof Ghanaat

URS Corporation

Englewood, CO

Guy Lund

Washington Infrastructure Inc

San Marcos, CA

Joe Ehasz

Halcrow Group Limited

United Kingdom

Dr. Shahin Ghanooni

BC Hydro

Burnaby, BC, Canada

Charles Holder

National Organizations

Association of State Dam Safety Officials (ASDSO)

Susan Sorrell

United States Society of Dams (USSD), Seismic Aspects of Dams Committee

Joe Ehasz

National Laboratories

Lawrence Livermore National Laboratory

Livermore, CA

Chad Noble

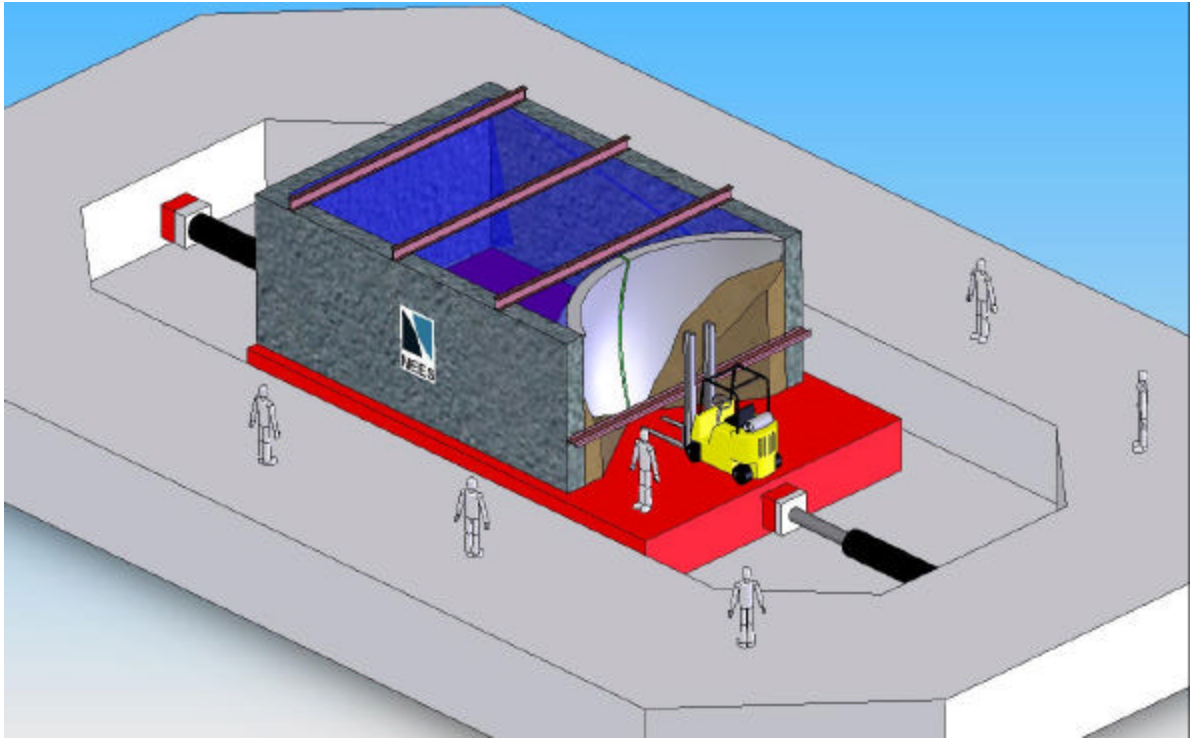


Figure 1 – This is a conceptual illustration of a possible large scale dynamic test of an arch dam on the NEES shake table at the University of San Diego. The size of the shake table permits the largest arch dam model ever tested in the United States. At this large scale, problems with similitude and scaling down many aspects of the dam, water, foundation, and load characteristics are reduced. Results from this test would provide invaluable validation of the seismic response of dams and reliability and accuracy of current numerical methods.

Of course, this model could be modified to test the soil-structure interaction against spillway walls next to embankment dams, embankment dams, and levees.

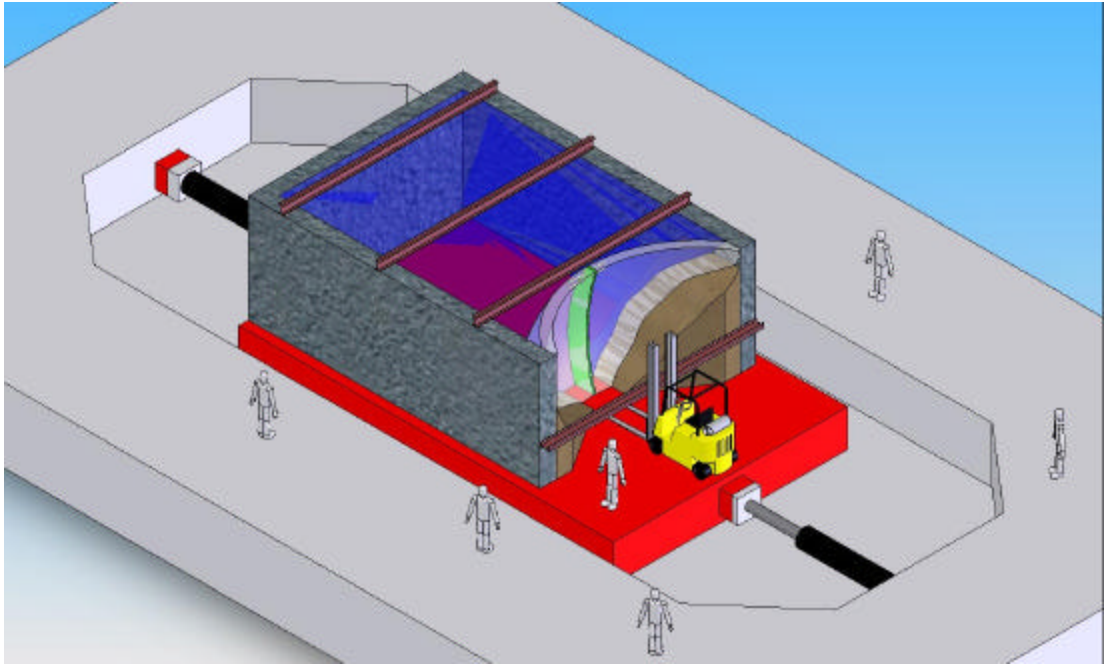


Figure 2 – This figure shows a transparent arch dam to better show the shape. At this large scale, contraction joints, lift lines, and “real” concrete can be incorporated.

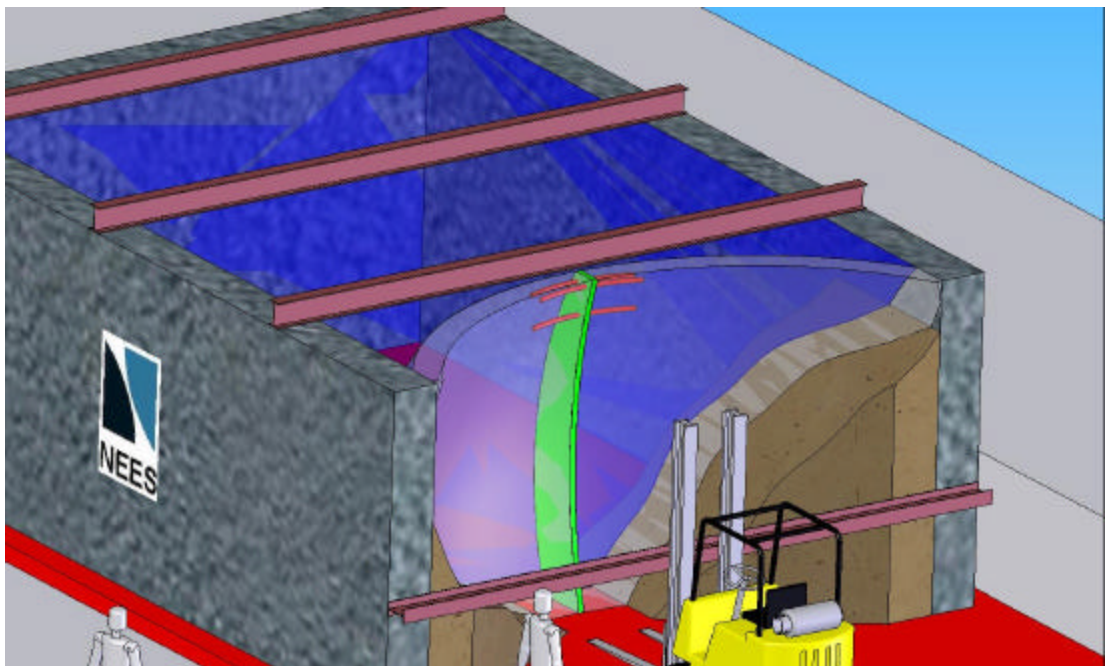


Figure 3 – There are many concepts to strengthen an arch dam in high seismic areas. These concepts could be validated with large scale testing.

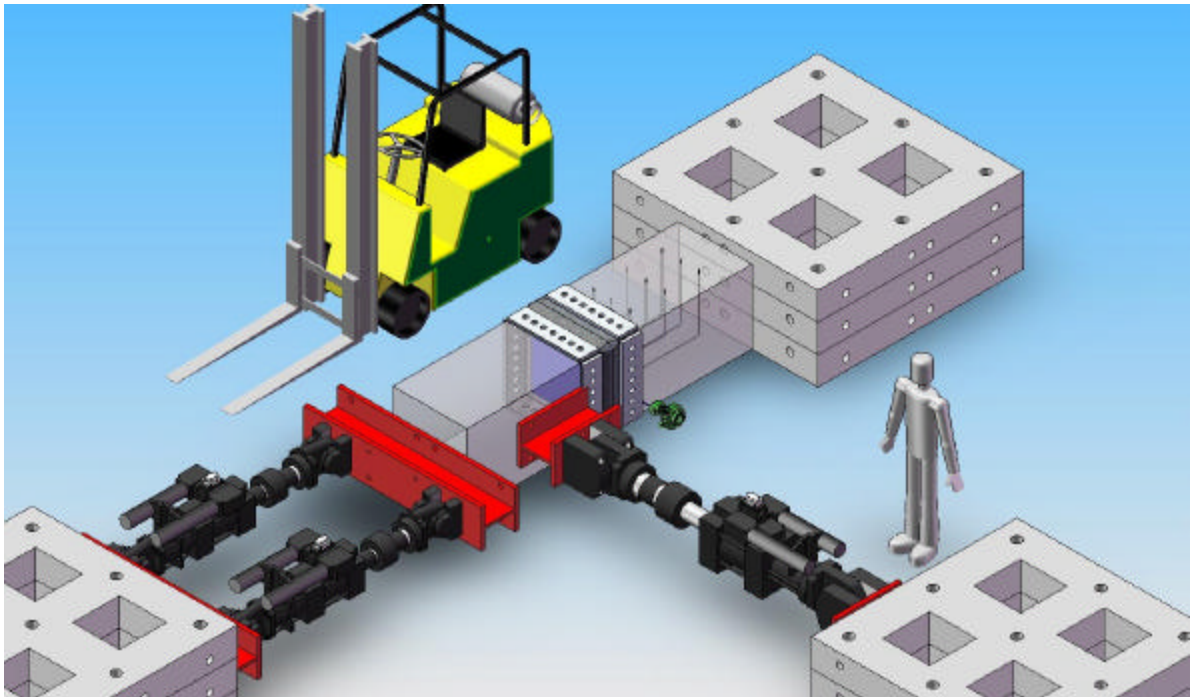


Figure 4 is an illustration of a potential fast hybrid test to determine the dynamic uplift in dams. The dam and foundations are modeled on the computer, whereas the joint is physically modeled in the laboratory. At each time increment, the computer sends a command to the actuator to impose a displacement to the pressurized joint, sensors record the dynamic uplift, and those are returned to the finite element analysis which can proceed to the next time step.

The joint, subjected to constant shear and a linearly varying normal stress, is pressurized for up to 300 feet of hydrostatic pressure, and piezometers record the internal pressure variation.